Tracking of Rapidly Time-Varying Sparse Underwater Acoustic Communication Channels

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LONG-TERM GOALS

The long-term goal is to develop, for broadband short-range very shallow water environment, dynamic channel estimation and equalization algorithms that can improve the receiver performance for phase coherent acoustic communications.

OBJECTIVES

That the broadband short-range shallow water channels can be both rapidly fluctuating and sparse poses significant challenge to the problems of channel estimation and equalization. The primary scientific objectives of this task are to:

1. Understand and establish the connections between the channel characteristics (deterministic and stochastic dynamics caused by signal interactions with surface gravity waves, implicit and explicit multipath sparseness due to broadband transmission and correlated surface scattering) and the performance of dynamic channel estimation algorithms and channel estimate based equalization algorithms.

2. Develop dynamic channel estimation algorithms that have improved tracking capability and are also robust to the channel sparse structure; Analyze the performance of these algorithms as related to the channel characteristics.

3. Develop equalization algorithms that are based on or combined with the dynamic channel estimation algorithms in an iterative fashion, for phase coherent signal demodulation.

APPROACH

The approach for this research is to combine experimental data analysis with analytical derivations.

The data obtained from the Wavefronts II experiment are representative of the broadband short-range shallow-water environment therefore serves a testing ground for the new algorithms. To achieve the first objective, data processing including estimation of the channel impulse response and the time-varying scattering function as well as channel estimate based equalization are carried out first. The

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characteristic scales of the channel dynamics and sparseness are then extracted from the channel estimates and associated with the signal prediction error and the soft decision error. The work also involves analytical derivation of these errors in terms of the characteristic scales which are then compared with the experimental data processing results.

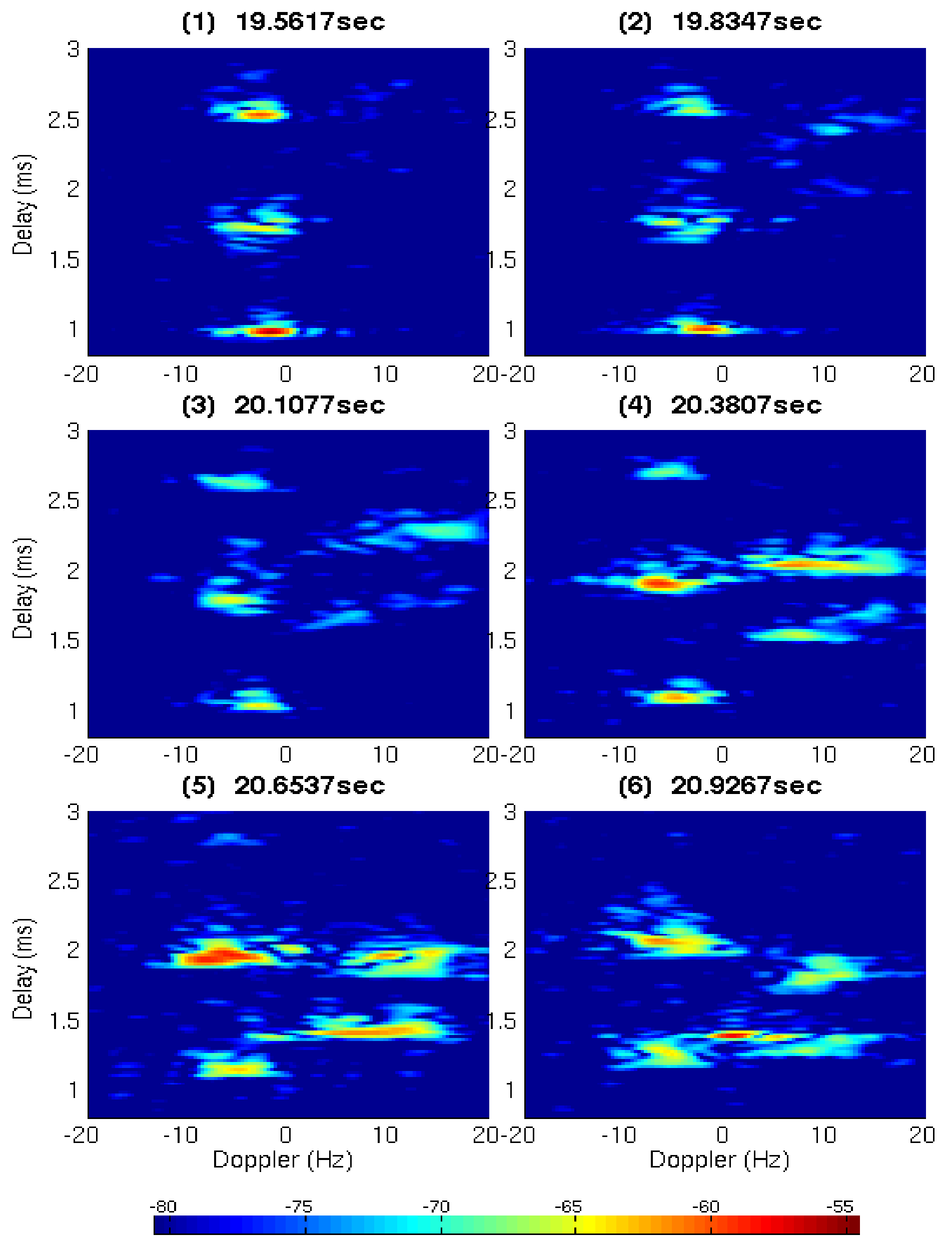
The second and third objectives are achieved through several steps including: i) the derivations of dynamic model based channel estimation algorithms and the iterative equalization algorithms; ii) the analysis of the behavior of these algorithms and the identification of the performance limiting factors; iii) the development of suboptimal but efficient implementations of these algorithms; iv) the testing of these algorithms on the experimental data.

WORK COMPLETED

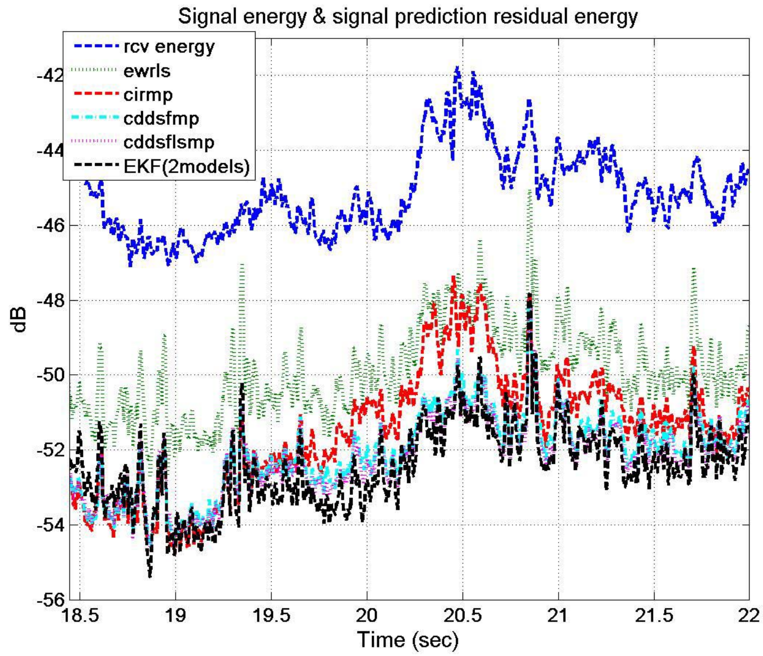
The work on channel estimation and equalization based on an explicitly sparse delay-Doppler spread function representation has been completed and a paper has been submitted. Analysis of model based dynamic channel tracking algorithms including extended Kalman filtering (EKF) and expected maximization (EM) algorithms has led to the discovery of an extended persistent excitation condition for the identification of the channel dynamic parameters. Based on this analysis, a two-model EKF algorithm has been developed and tested on the experimental data.

RESULTS

We have found that the combination of the rapid channel fluctuations and sparse multipath structure poses the real challenge to the problems of channel estimation and equalization and that both need to be addressed simultaneously in order to successfully track the channel using dynamic model based approaches. An extended persistent excitation condition has been obtained through the analysis of the EKF and EM algorithms for joint channel and parameter estimation. The condition indicates that the indiscriminative tracking of all components of a sparse channel is unreliable and prone to algorithm divergence. This can be intuitively interpreted as saying that the problem of identifying the dynamics of something having little energy is an ill-defined one. Motivated by this, a two-model based EKF algorithm has been developed which selectively tracks the dominant channel components. The experimental testing results demonstrated that the algorithm is robust to both channel rapid fluctuations and sparseness. Another effort to address the dynamics and sparseness combination has led to the development of sparse estimation of the channel delay-Doppler spread function. The testing results have shown that the amount of performance improvement it provides is equivalent to that of the two-model EKF algorithm.



A sequence of time-varying scattering function estimates, obtained as a large surface wave approaches and eventually reaches the specular point of the first surface arrival. The delay region corresponds to the first three surface arrivals. These plots clearly show the two aspects of the channel that this work tries to address: rapid fluctuations and sparse structure.



Signal prediction residual errors obtained using various channel estimation algorithms: (EWRLS: channel impulse response estimation using the exponentially weighted recursive least squares; CIRMP: Matching Pursuit channel impulse response estimation; CDDSFMP & CDDSFLSMP: Matching Pursuit and order-recursive least squares Matching Pursuit estimations of the delay-Doppler spread function; EKF(two-models): channel impulse response estimation using the two-model based EKF algorithm. The top curves in blue color is the total energy of the received signal.

IMPACT/APPLICATIONS

The development of the new dynamic channel estimation algorithms will be very useful in improving the robustness of high-speed phase coherent reception in very shallow water environment where the surface scattered components introduce rapid channel fluctuations. The formulation of the extended persistent excitation provides the theoretical basis that explains intuitively the pitfall of dynamic tracking of a generally sparse broadband multipath channel. It has also motivated the development of a class of sparsely constrained dynamic tracking algorithms which not only have direct application in the current problem but also have important implication for other applications where the combination of dynamics and sparseness poses competing requirements.

TRANSITIONS

None.

RELATED PROJECTS

This work continues from Weichang Li's Ph. D. thesis research which was supported by the ONR project N00014-05-10085.

PUBLICATIONS

W. Li, J. Preisig ``Estimation of Rapidly Time-Varying Sparse Channels" in IEEE Journal of Oceanic Engineering, 2006. [submitted, refereed journal]

W. Li, J. Preisig `` Estimation and Equalization of Rapidly Varying Sparse Acoustic Communication Channels" in IEEE-MTS Oceans Conference 2006, Boston, MA, September 18-22, 2006. [published, refereed conference]

W. Li, J. Preisig ``Vector Form EM and Suboptimal Joint State and Parameter Estimation" in Proceedings ICASSP 2006, Philadelphia, PA, March 19 - 23, 2005, Vol 4, pp.~313 - 316. [published, refereed conference]